Historic, archived document

Do not assume content reflects current scientific knowledge, policies, or practices.

WORKING PLAN FOR FIRE BEHAVIOR STUDIES IN THE COASTAL PLAINS OF THE SOUTHEAST

by
George M. Byram, Physicist
Southeastern Forest Experiment Station

August 1, 1950

RMRS Library
USDA Forest Service
AUG 3 2007
240 W Prospect Rd
Fort Collins CO 80526

TABLE OF CONTENTS

SUPPLEMENT 1 - Working Plan for Determining the Lethal Temperature of Loblolly Needles and Buds.

SUPPLEMENT 2 - Working Plan for Determining the Effect of Initial Stem Temperature on the Size and Age of Hardwoods Killed by Fire.

SUPPLEMENT 3 - Theoretical Analyses.

SUPPLEMENT 4 - Statistical Analyses.

SUPPLEMENT 5 - Bibliography and Review of Literature.

INTRODUCTION

This report covers our present fire behavior and related studies in the coastal plains of the southeast and will form the basis for work in fire behavior for the next two years. It replaces the working plan for fire intensity investigations which was written in 1947. Some of the earlier problems have been solved, others partially solved, and new problems have come up. The main purpose of this analysis is to formulate the various problems, to establish their relation to each other, and to appraise their relative priorities.

A discussion of the work of the past two years is also given so this analysis is therefore in a sense a progress report. Discussion of work of the past two years will be given in Section I. The discussion in Section II concerns the application of the findings in Section I to the possible role of prescribed fire in the life cycle of loblolly and longleaf pine. Also Section II is based in part on the results of the prescribed burning program on the Francis Marion National Forest and on the results of studies by the Santee Experimental Forest personnel. It should be pointed out that the suggestions in Section II as to the use of prescribed fire in the life cycle of loblolly and lonfleaf pine are tentative and will undoubtedly be modified as later studies are completed. However, there seems to be no good reason for waiting until all studies are complete before attempting

to unify and apply what we already know or even partly know. Section III constitutes the major part of the analysis and concerns primarily the discussion of problems and studies for the next two years.

Our original plans were to concentrate our efforts on the more direct studies of fire, its behavior (fire intensity in particular), and some of the basic relations between fire and the living tree. There seems to be no reason as yet to modify this general approach. Fire can be considered as one of the highly variable elements of ecology having equally variable and diverse effects on the forest areas through which it burns. One objective of the work planned in 1947 was to determine how fire intensity was related to the fuel characteristic variables (fuel density, fuel size, and fuel compactness) and the physical variables of fuel moisture, fuel temperature, and wind velocity. Another objective of this early work was to determine how the lethal effects of fire on living vegetation are brought about. As work progressed it soon became apparent that from the standpoint of their application in the prescribed burning program, problems concerning the basic relations between fire and the living tree were more important than those associated with the first objective. The basic work on problems in this second group is completed, and more time can now be given to larger scale studies and to the pure fire behavior problems.

At the present time we believe the problem of the behavior of severe fires has higher priority than any other study. The pronounced change now occurring in the stand and fuel types of extensive areas in the South will make these fires more serious in the future than they have been in the past. The problem of severe fires is doubly important because fire fighting methods and a suitable fuel type rating system will depend on its solution.

SECTION I - Report on Work for the Period 1947-50

Procedure

A preliminary theoretical analysis was made in 1947 on heat transfer and the temperature rise in the critical parts of a living tree. This analysis indicated clearly how the damaging and lethal effects of fire are brought about. It also indicated the nature and design of the field experiments needed to verify the predictions of the theoretical analysis.

The theoretical analysis revealed an important relation between fire and its lethal effects on living trees. This relation was an indirect one in that the damaging effects of fire would depend as much if not more on the initial temperature of the critical parts of the tree as on the intensity of the fire itself. It is known that the lethal temperature of plant tissue is in the neighborhood of 140 F, and this is the value used in our computations. A study of the lethal effects of fire thus reduces to a study of those factors and combinations of factors which will cause the temperature of the needles, buds, twig endings or cambium layer to exceed 140 F. One of the most important of these factors is the initial vegetation temperature because it determines the amount of intrinsic energy or heat. Pine crowns at a temperature of 100 F will continue to thrive and grow, yet at that temperature they already contain most of the heat required to kill them. Pine needles at a temperature of 100 F require only half as much heat to raise their temperature to 140 F as do pine needles at

an initial temperature of 60 F. This is a somewhat over simplifed description of the effect of vegetation temperature on mortality, but it illustrates why trees can tolerate higher intensity fires in cold weather than in warm weather. A detailed description of vegetation temperature and the heat transfer process are given in Supplement 3.

Because the lethal effects of a fire are determined by the initial vegetation temperature and the quantity of heat which flows into the critical parts from the fire, the fire intensity study was designed to yield information which would describe the heating effects of a fire in terms of these key variables. The amount of heat transferred to these critical parts depends on the temperature of the hot gases and the length of time that the needles and buds are enveloped by the gases. However, by using a heat receiver with about the same heat capacity as the buds and small twig endings, the time effect can be integrated into a single measurement. For example, thermometer bulbs placed at different heights above a fire and having a heat capacity about equal to that of loblolly pine buds will determine the heat factor at those heights. A temperature reading is obtained but it is not the temperature of the gases above the fire. The temperature rise corresponds to a quantity which may be defined as a heat factor and is directly proportional to the quantity of heat which is transferred to the buds.

During the early part of the field work, measurements were made with No. 8 (B & S gauge) chromel-alumel thermocouples. Four thermocouples were arranged vertically at heights above the ground ranging from 1 to 8 feet and were all connected to the same pyrometer by means of selective switches. It was soon found that the temperatures above a backfire were considerably lower than expected, and with few exceptions it appeared that it might be possible to use ordinary glass bulb thermometers without much danger of breakage. Thermometers (maximum registering) with a 0 - 150 C range were tried and found very satisfactory. In backfires they could sometimes be placed within 2½ feet of the ground without breaking. Because thermometers are considerably easier to handle than thermocouples, they were used for all later measurements except when it was desirable to know the rise and fall of temperature as the fire spread past a given reference point.

On each test burn, a fuel sample of one square yard was taken and its oven dry weight obtained. The moisture content of the upper and lower fuel was determined. Vegetation temperature was measured by thermometers with bulbs painted green with about the same reflectance as the green pine foliage. Fuel temperature was measured and wet and dry bulb temperatures gave the relative humidity. Wind velocity was measured at a height of about 3 feet above the ground in order to obtain the velocity controlling the tilt angle of the flames. When

burns were made on the loblolly area, the height of the scorch line was observed after a week or more had elapsed since the burn.

All of the study areas selected were on the Francis Marion National Forest in South Carolina. One area of about 30 acres had a stand of young loblolly pine which is now about 10 years old. This area was comparatively free of young hardwoods and evergreen shrubs - consequently it had fairly uniform fuels. The composition of these fuels ranged from grass, through varying mixtures of grass and pine straw, to pure pine straw fuel in the dense thickets. The photograph in Figure 1 shows a more open part of this area. All plots on this area were burned with backfires and were 75 feet square. It had been originally planned to burn some plots (150 feet square) with headfires, but measurements from the backfires indicated that headfires would have given scorch lines higher than many of the trees on the plots, so would have contributed little to the progress of the study.

The other area was a comparatively open longleaf ridge (see photograph in Figure 2) with a scattering of mature trees (longleaf) which had been left when the area was cut over some 15 years before. The area was thinly stocked with reproduction ranging from 2 to 12 feet in height. It was on the whole densely stocked with seedlings in the grass stage. Fuels on the area were even more uniform than on the loblolly study area. They consisted either of grass or grass and pine straw mixtures. The majority of test burns for fire intensity measurements were on this area because of the more uniform fuels and wider range of wind velocities. Also grass fuels in the

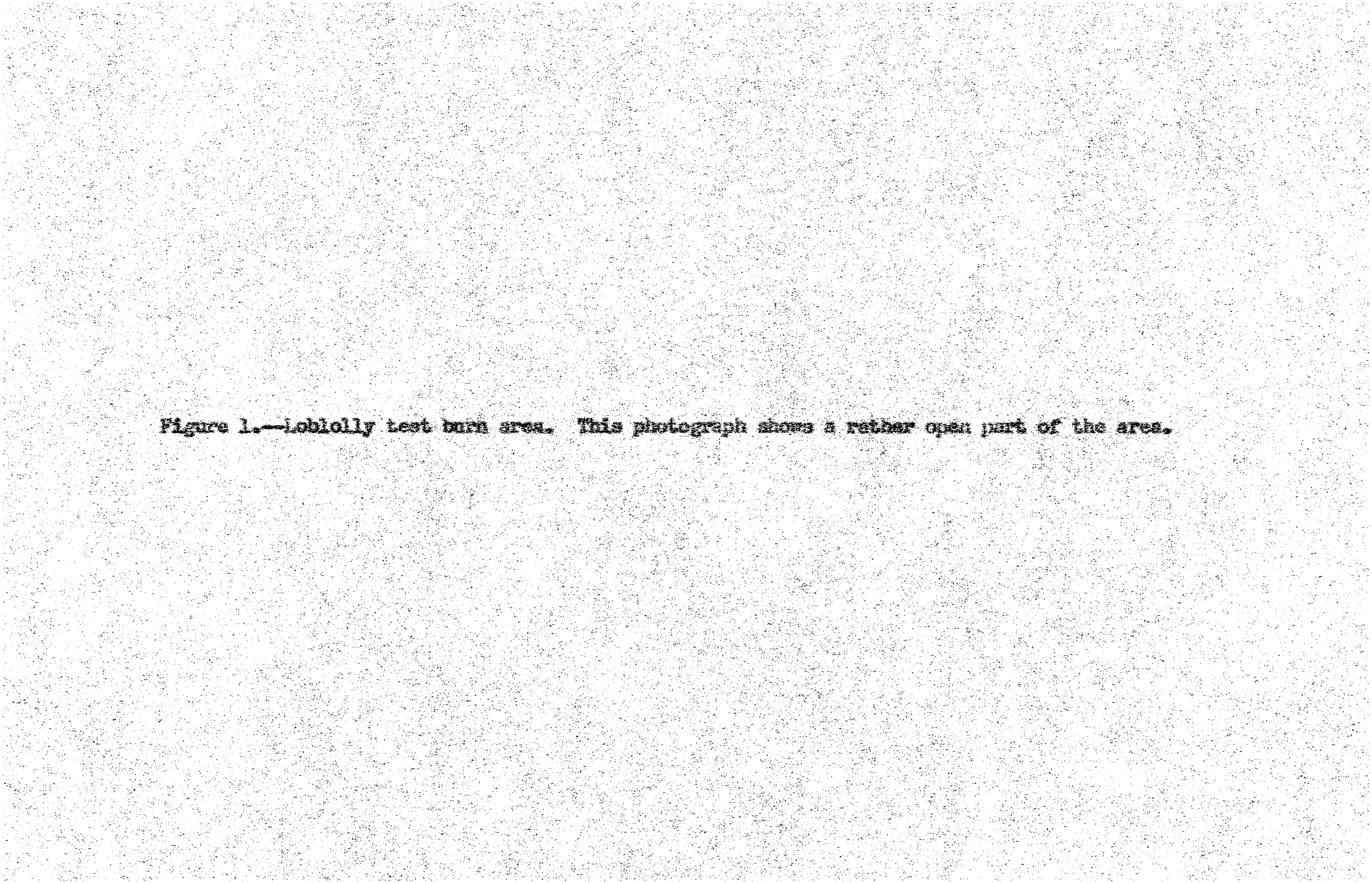


Figure 1.--Loblolly test burn area. This photograph shows a rather open part of the area.

Figure 2.—Longleaf fuels in open type of stand.

open dry out rapidly after a rain, so it was possible to burn here in weather when burning would not have been possible in a loblolly stand. However, all burns made to determine the relation between height of scorch line and fire intensity were made on the loblolly area.

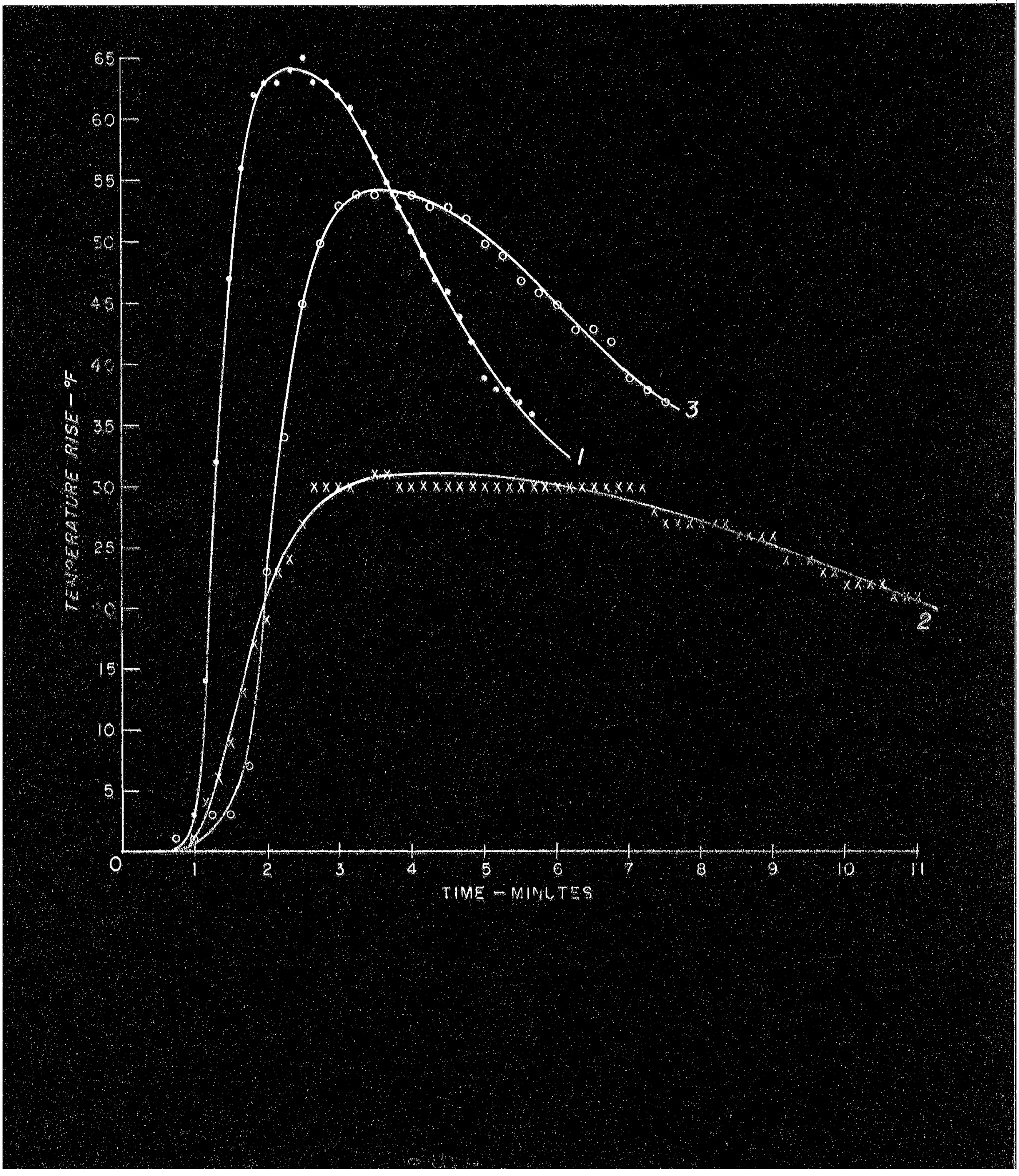
Analysis and Discussion of Results

Longleaf seedling temperatures

If a tree survives a hot fire it is certain that the critical parts of the tree did not exceed the lethal temperature (about 140 F) regardless of how intense the fire was. This statement may be regarded as a corrollary to the definition of lethal temperature. Figure 3 shows the temperature rise in the buds of longleaf seedlings when backfires passed over them. These temperatures were measured with copper-constantan thermocouples made of fine wire inserted in centers of the terminal buds of the seedlings. It will be noticed that the temperature rise is very small considering that the seedlings were enveloped for several seconds by flames having a temperature in the nieghborhood of 1500 F which burned off almost all their needles.

The temperature of a seedling shows no measurable rise until the flames have almost reached the seedling. The temperature then rises rapidly, reaches a maximum, and cools very slowly. The seedling still contains a large part of the heat contributed by the flames 10 minutes after the fire has passed. Curve #1 shows the rise and fall of temperature in a seedling of low vigor with a sparse cluster

Figure 3.—Temperature rise in the buds of three longleaf pine seedlings burned with backfires.



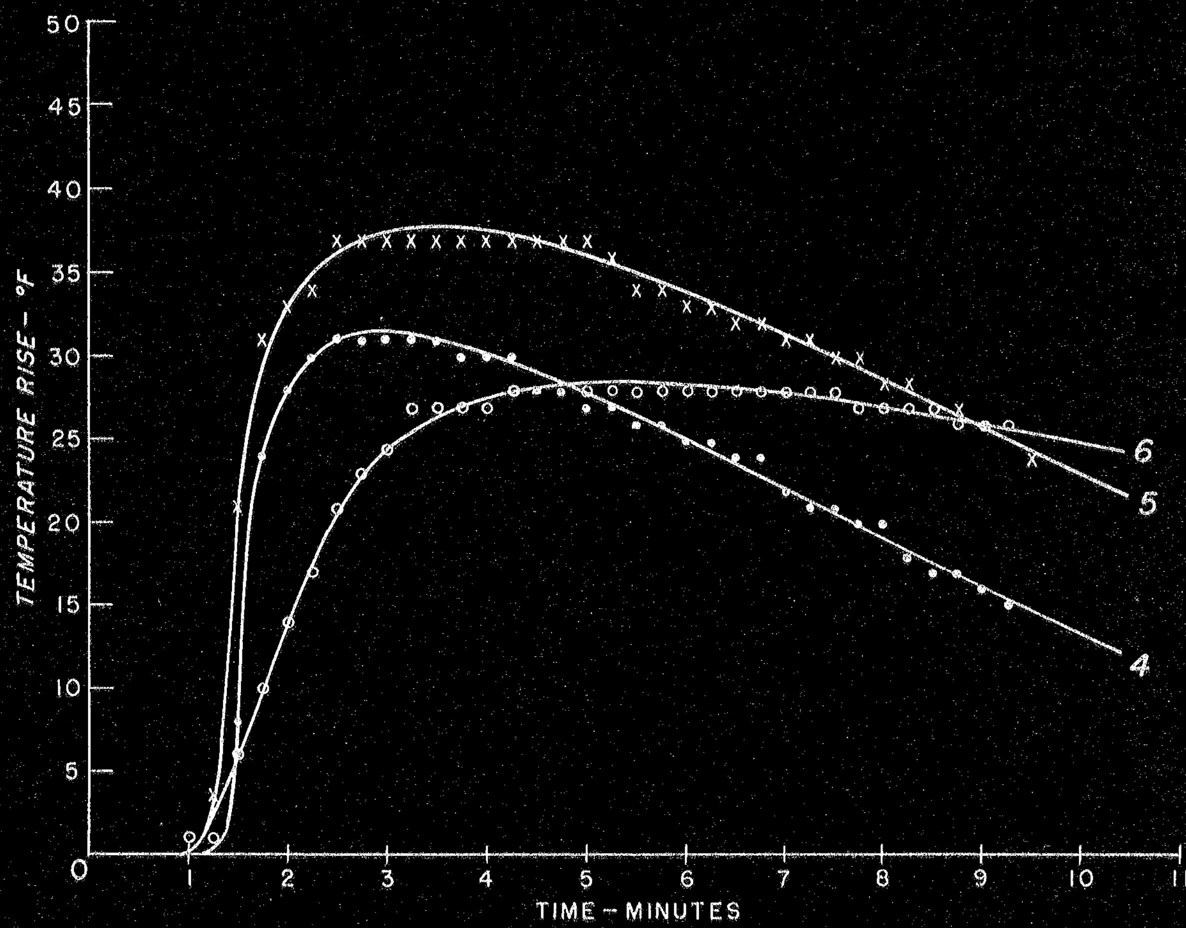
TEMPERATURE RISE — °F
TIME — MINUTES
0
65
60
55
50
45
40
35
30
25
20
15
10
5
1
2
3
4
5
6
7
8
9
10
11
1
2
3

of shielding needles. Curve #2 is for a vigorous seedling with a heavier bud and a denser sheath of shielding needles. Curve #3 represents an intermediate seedling.

The curves in Figure 3 are plotted in terms of temperature rise in the seedling bud rather than in terms of actual temperature. This procedure makes it possible to estimate readily the effect of initial temperature on seedling mortality, because the shape of the curves is almost independent of the initial temperature of the seedling. For example, the bud of seedling #1 had an ultimate temperature rise of 65 F. Substracting this figure from the lethal temperature of 140 F gives 75 F as the maximum initial temperature the seedling could tolerate. Stated in another way, a seedling with an initial temperature of 75 would require a temperature rise of 65 F to reach the lethal temperature of 140 F. If the initial temperature was less than 75 F, the seedling should survive. On the other hand seedling #3 had an ultimate temperature rise of only 31° F. This seedling should therefore be able to tolerate an initial temperature of about 109 F.

Figure 4 shows a similar set of curves for headfires. The form of the curves is almost identical with that of the curves in Figure 3 although the ultimate or maximum temperature rise for the headfires is not as high. However, it is likely that this difference between the two sets of curves has no special significance. Probably it is a result of differences in fuels and slight differences in

Figure 4.—Temperature rise in the buds of three longleaf pine seedlings burned with headfires.



TEMPERATURE RISE - °F
TIME - MINUTES
50
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
6
5
4

seedling size. Backfires are hotter than headfires near the ground as will be shown in the next topic but the difference is not large enough to be significant in the present experiment. A large number of measurements of seedling temperatures would be needed to show the headfire-backfire effect which can be determined better by other methods.

It was noticed that most of the two year old seedlings were killed in the experimental burns on the longleaf area. From the curves in Figures 3, 4, and 7 and the computations in Supplement 3, the temperature rise for these small seedlings should be about 95 F for the headfires and about 105 F for backfires. Since most of the burns were made when the air temperature was between 65 F and 80 F it is likely that the majority of these seedlings were heated above the lethal temperature. For these seedlings to survive, their initial temperature at the time of the fire probably should not exceed 50 F for headfires nor 35 F for backfires. At night and on cloudy days the seedling temperature does not differ greatly from the air temperature. On sunny days it should be remembered that the temperature of partially shaded seedlings in the grass may be from 5 F to 10 F higher than the air temperature.

The seedlings on which the bud temperature measurements were made were all about the same size and just starting to put on height growth. They averaged about 3 inches in height and their terminal buds were about ¼ inch in diameter. The quantity of fuel is probably

one of the most important factors in determining the temperature rise in longleaf seedlings and on this area was about 2 tons per acre (3-year old rough). A heavier fuel, say 3 or 4 tons per acre, should have resulted in a considerably larger temperature rise. Unless the moisture content is high enough to inhibit the combustion process, fuel moisture content probably does not have a pronounced effect on seedling temperature rise in a grass fuel. If grass burns at all, it burns almost completely regardless of fuel moisture and the total energy released should be nearly constant. However, the dense smoke given off at high moisture contents indicates some decrease in combustion efficiency.

Mortality in longleaf beginning height growth

When longleaf pine is from 1/2 to 4 feet in height it is rather susceptible to fire. On hot days mortality may be as high as 70 or 80 percent for the smaller trees. It is often thought that bud injury is one of the main causes of mortality, but the measurements described in the preceding topic indicated that fire might not as a rule injure the buds on thrifty young longleaf. If this is true, then the next most logical fire injury would be girdling near the base of the main stem. Until longleaf pine has reached a height of 6 or 7 feet, most of its needles grow radially from the main stem. When these needles drop they form a mound of heavy fuel around the stem base. When this concentration of fuel burns, embers will glow near the bark of the tree for several minutes after the fire has passed.

Whether mortality is caused by girdling or bud damage will have considerable bearing on the type of fire most suitable for prescribed burning. For this reason, an experiment was performed to determine which of these two factors was the primary cause of mortality. One hundred trees, varying in size from 1½ feet to about 4½ feet, were selected and were numbered at random. The two acre plot was divided into two nearly equal plots, one of which was burned with a backfire and the other with a headfire. On each plot 25 trees (selected at random) had the base of their stems insulated up to a height of one foot with aluminum foil. On the other 25 trees the terminal buds were protected by tying the heavy needle sheaths over the buds. These two treatments are shown in Figures 5 and 6.

The results are summarized in Table I. One tree with the buds insulated could not be located. Eleven trees with the base of the stems insulated were discarded because the high wind blew off the aluminum foil when it became softened by the fire. The results (highly) significant) show that girdling at the base of the main stem is undoubtedly the main cause of mortality. Since determining the difference between these two treatments was the main purpose of the experiment, the backfire and headfire data were combined in Table I. The statistical analysis is given in Supplement 4.

Table II shows the backfire and headfire data tabulated separately. Mortality was not high enough to show any significant difference between the two types of fires, and an experiment intended

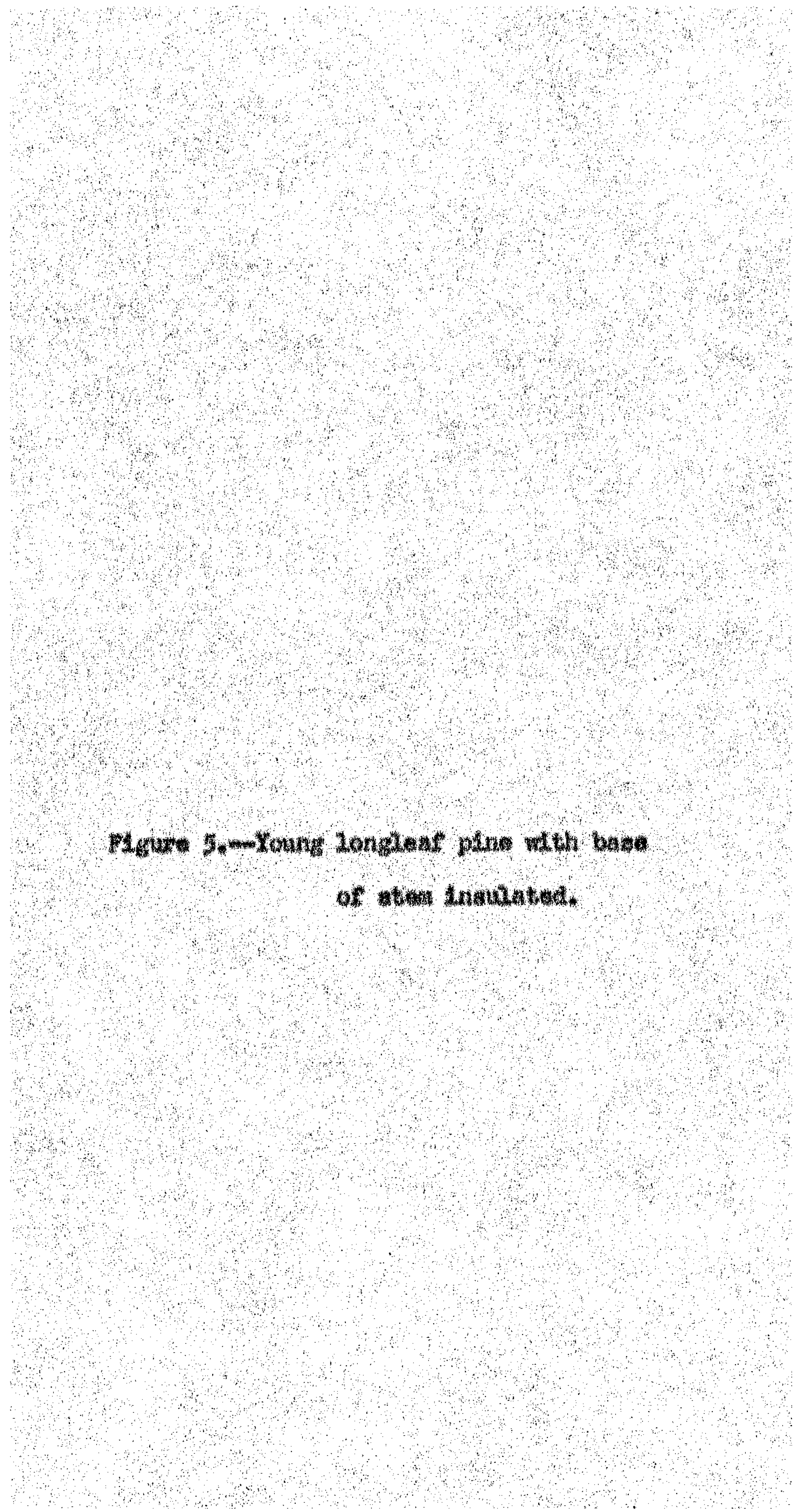


Figure 5.--Young longleaf pine with base of stem insulated.

Figure 6.—Young longleaf pine with terminal buds insulated.

primarily to show this difference would have a considerably different design. However, the results do indicate that there is probably little difference between the lethal effects of headfires and backfires for longleaf pine in this size class. Considering that the trees on the headfire plot were somewhat larger than on the backfire plot, it may be that the lethal effects of headfires are slightly greater in this size class. If a difference exists it is undoubtedly small compared to that which a change in initial tree temperature would produce. It was noticed on the headfire plot that on many trees the fire had injured a narrow vertical strip of the cambium on the leeward side of the tree up to a height of several feet. Pitch was coming from this strip which had a width equal to about 20 percent of the stem circumference. The injury of this narrow strip seemed to have no adverse effect on the tree.

One 3-foot tree in the headfire plot which was classed as "dead" was found to be putting out sprouts in the lower one foot zone which had been covered by the aluminum foil. From the appearance of this tree it had apparently been girdled higher on the stem.

It is surprising that intense headfires do not have more serious effects on longleaf saplings. This plot was burned with a 9-mile wind which produced flames that reached a height of 15 feet. The corresponding backfire which produced almost the same results had flames which did not exceed a height of 2 feet.

TABLE I. Data showing a comparison of the effects of two different insulating treatments on the mortality of young longleaf pine. Headfire and backfire data are combined. Heights are given in feet.

	Base of stem insulated			Terminal buds insulated		
	Alive	Dead	Total	Alive	Dead	Total
Number	35	4	39	33	16	49
Percent	90	10	100	67	33	100
Av. height	2.98	3.38	3.01	3.09	2.49	2.90

Table II. Data are similar to those of Table I except that headfire and backfire data are tabulated separately.

Backfire

	Base of stem insulated			Terminal buds insulated		
	Alive	Dead	Total	Alive	Dead	Total
Number	20	2	22	17	7	24
Percent	91	9	100	71	29	100
Av. height	2.58	2.65	2.57	2.98	2.33	2.79

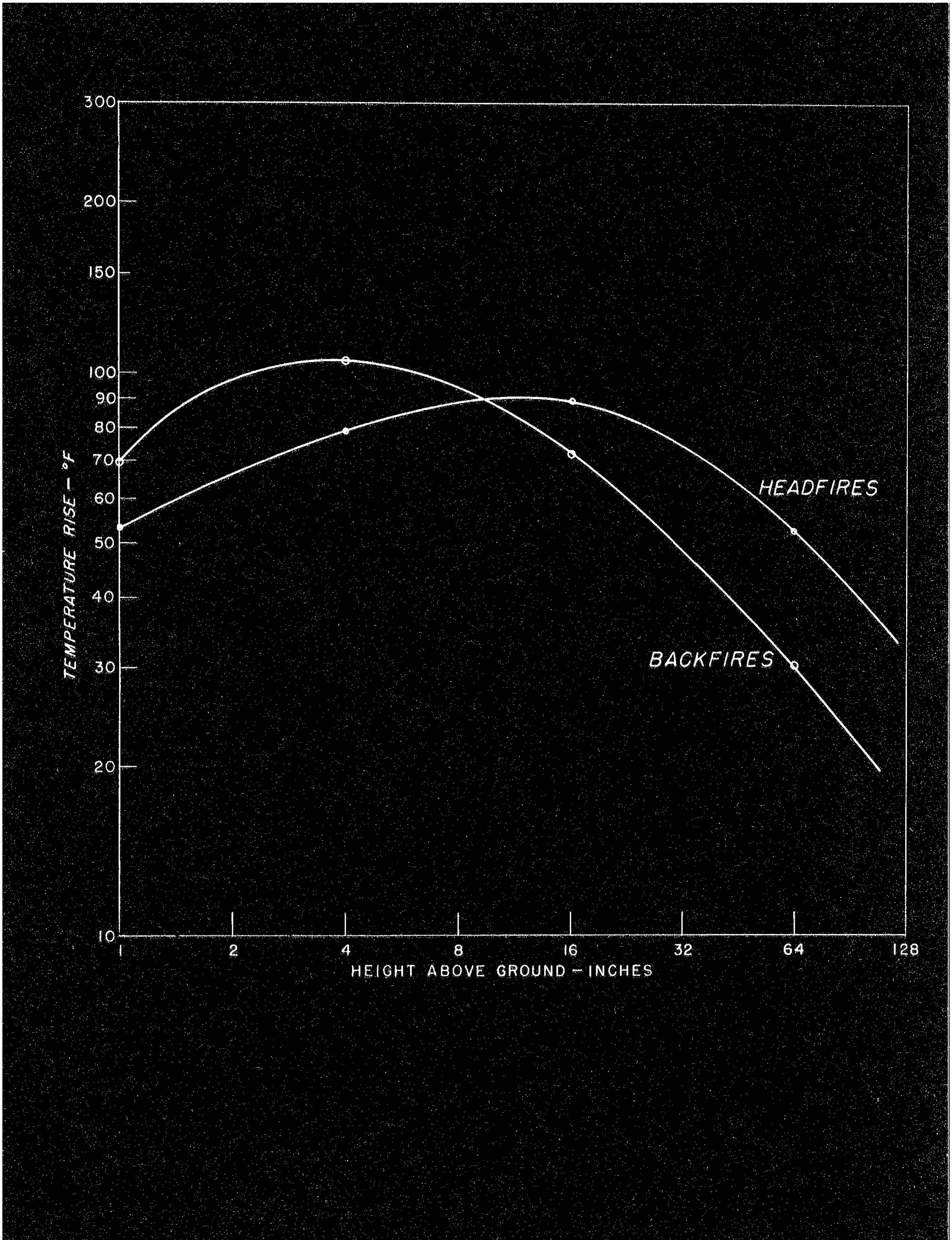
Headfire

	Base of stem insulated			Terminal buds insulated		
	Alive	Dead	Total	Alive	Dead	Total
Number	15	2	17	16	9	25
Percent	88	12	100	64	36	100
Av. height	3.51	4.10	3.58	3.21	2.62	3.00

Temperatures of headfires and backfires

The relative heating effects of backfires and headfires burning under identical conditions have been determined. Work on this problem was prompted primarily by some observations of the personnel of the Francis Marion National Forest who had been active in prescribed burning work. From their field experience they felt that slow spreading backfires might be hotter close to the ground than fast spreading headfires. Preliminary thermocouple measurements on fires in the spring of 1948 indicated that this was true. The same result was obtained in the fall of 1949 when the experiment was repeated with improved equipment and a larger number of measurements. Furthermore it was found that headfires spreading before a strong wind are cooler near the ground than headfires spreading before a light wind. The results of the later tests are shown in Figure 7. In these measurements, high temperature maximum registering thermometers were insulated by rolling them in paper and inserting them in a double wall iron pipe. The double wall pipe consisted of a 1/4-inch iron pipe inside a 5/8-inch pipe with an air space between the two. A plaster of paris plug closed the end of the 1/4-inch pipe next to the thermometer bulb. With their sensitivity reduced in this manner, the thermometers responded to fire in about the same way as longleaf seedling buds - that is, the reading of temperature rise was directly proportional to the heat factors. The thermometers were placed at heights of 1 inch, 4 inches, 16 inches, and 64 inches above the ground. One set of four

Figure 7.--Temperature rise at different heights above ground for headfires and backfires. Measurements were made with shielded thermometers.


300
200
150
100
90
80
70
60
50
40
30
20
10
TEMPERATURE RISE - °F
HEADFIRES
BACKFIRES
1
2
4
8
16
32
64
128
HEIGHT ABOVE GROUND - INCHES

thermometers was placed in the backfire plot and another in the headfire plot. The headfire and backfire burned simultaneously or nearly so.

It will be noticed that the curves in Figure 7 are plotted on a log-log scale which has the advantage of expanding these parts of the curves representing heights near the ground. In this case the log-log plot gives much simpler curves than does the usual linear method of plotting. Each point is the average of four measurements (four backfires and four headfires). At heights less than 10 inches, backfire temperature readings were higher than headfire readings. Both curves show a cool zone next to the ground. The backfire curve has a maximum at a height of 4 inches and the headfire curve a maximum at about 12 inches. The first measurements in 1948 had indicated that the maximum was nearly the same (about 4 inches) for both curves and that their intersection came at about 20 inches. However, the curves in figure 7 representing the 1949 measurements are probably more reliable.

It should be pointed out that the difference between the two curves in Figure 7 should be greater for a headfire-backfire pair burning in a strong wind than for a pair burning in a light wind. This might also have some effect on the position of their relative maximum points as well as on the position of the point of intersection. No attempt was made to determine in detail the effect of wind velocity on the two curves, but the data obtained thus far indicate that the difference in the temperature rise between backfires and headfires

recorded at 4 inches increases with wind velocity. The statistical analysis is given in Supplement 4. The data also show some tendency for the temperature rise at the 4-inch level to decrease for both headfires and backfires with increasing wind velocity.

That backfires should be hotter than headfires near the ground seems logical from the nature of the combustion process in grass fuels. In a backfire most of the combustion occurs at the lower levels. The backfire burns away the base of the grass stems causing them to topple over and burn near the ground. In a headfire the upper fuels burn first and combustion occurs at a considerably higher level.

Crown scorching

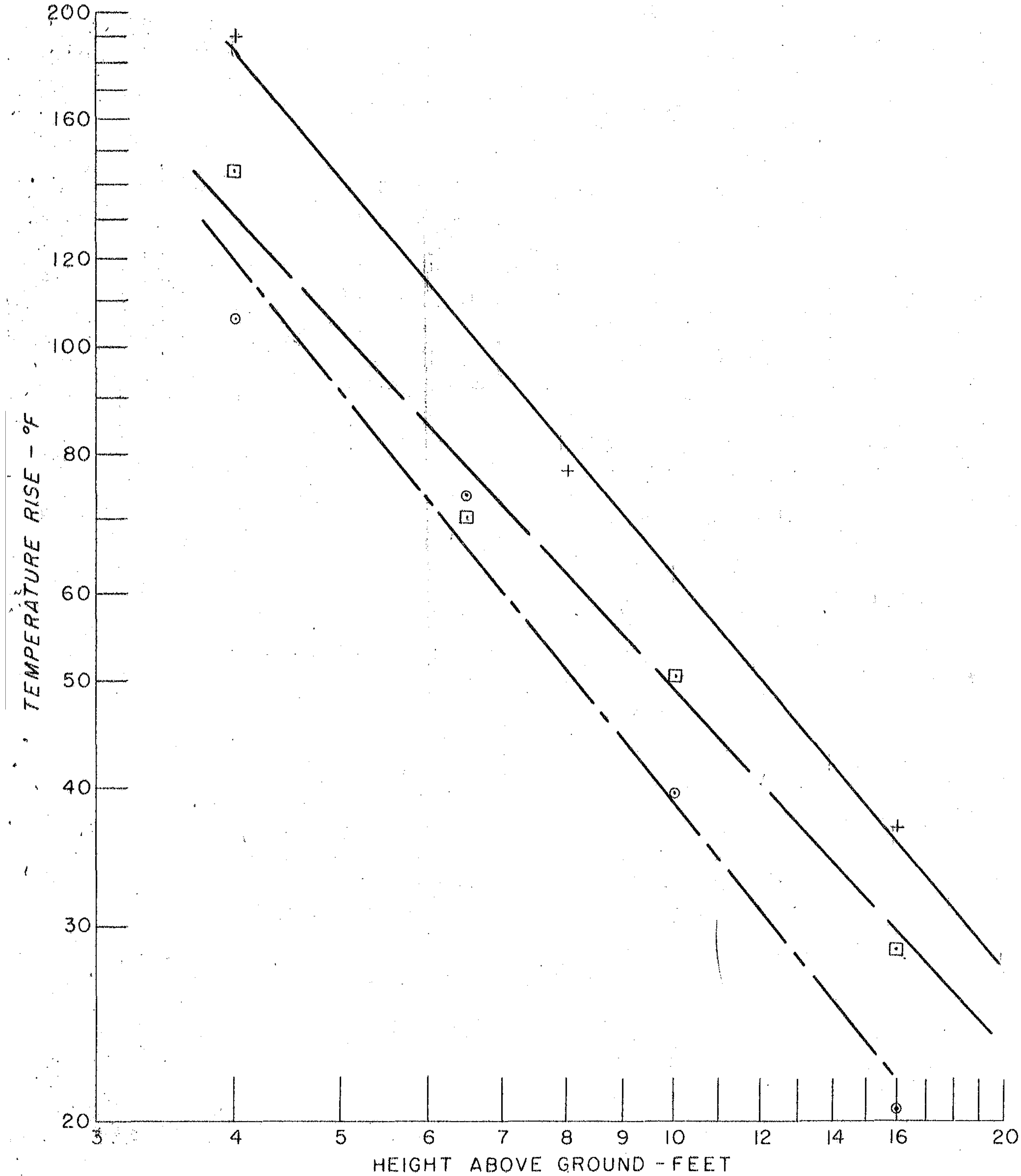
Mortality from fire in reproduction stands of pine, as well as in the larger stands, is determined primarily by the heating effects in the tree crowns. The critical parts of the crown such as needles, buds, and small twig endings will presumably die if their temperature exceeds the lethal value of 140 F. With the exception of suppressed trees with small stems and thin bark, the girdling effects of prescribed fire in the southern pines are probably of little importance. One other exception is mortality in young longleaf in the height class from 1/2 to 4 feet discussed in a previous topic.

The temperature of the gases above a fire decreases rapidly with height. Thermometers placed at different heights do not register the temperature of the gases but usually indicate a somewhat lower temperature which corresponds more closely to the temperature reached

by the buds and twig endings. The difference between the initial and maximum thermometer readings give the temperature rise. If the thermometer bulb has approximately the same heat capacity as the bud and twig endings the temperature rise should be directly proportional to the heat factor.

The temperature rise at different heights above the ground is shown for three different fires in Figure 8. These fires burned in an atmosphere in which there was some turbulence, and the fuels were considerably warmer than the air. The theory of the relationship between the temperature rise, height of thermometers, and fire intensity is developed in Supplement 3 where it is shown that the relationship between temperature rise and height above ground is linear when plotted on log-log paper. This prediction is supported by the curves in Figure 8. Figure 9 shows three additional curves plotted for fires which burned in a more stable atmosphere. Here also the linear relationship is evident, but the slope of the lines is less and there is a tendency for the points to curve slightly upward. The dashed curve is an extreme case. The fire which this curve represents burned on a calm, clear night when there was a pronounced temperature inversion in the lower atmosphere. The inversion was equivalent to a ceiling which the rising gases could not penetrate. They had a tendency to collect and level off at a height of about 30 feet. This may explain for this particular fire the peculiar increase of temperature rise observed with height. Had the air temperature been a few degrees

Figure 8.--Temperature rise with height of three fires.



200
160
120
100
80
60
50
40
30
20
TEMPERATURE RISE - °F
3
4
5
6
7
8
9
10
12
14
16
20
HEIGHT ABOVE GROUND - FEET

warmer it is likely that the tops of the tree crowns would have been scorched and the lower parts of the crowns undamaged. The air temperature was about 32 F and the only scorching observed was within 2 or 3 feet of the ground on small understory trees.

The lapse rate is difficult to measure unless the temperature can be determined accurately at a series of heights above the ground. Also, the importance of its possible effect on the slope of the curves in Figures 8 and 9 was not realized when the fire intensity studies were started. For these reasons no direct measurements of the lapse rate were made, and the state of turbulence for the fires represented by the curves in Figures 8 and 9 was estimated indirectly from wind velocity, time of day, fuel temperature, and lower air temperature. The slope of the curves in the curves in Figures 8 and 9 is probably affected to some extent by several factors, but the lapse rate is probably the most important of these.

The lapse rate is undoubtedly the dominating factor affecting the behavior of severe fires, especially after they reach a certain critical size. This will be discussed in more detail in Section III.

The height of the scorch line can be estimated from curves such as those in Figures 8 and 9 when the initial crown temperature is known. Also the relationship between height of scorch line, initial vegetation temperature, and fire intensity can be readily derived (see Supplement 3). Figure 10 shows how height of scorch varies with vegetation temperature. The curve is theoretical and was computed from Eq. 10 in Supplement 2. The plotted points represent observed

Figure 10.—The relation between height of scorch line and initial vegetation temperature. Fires are all reduced to same intensity.

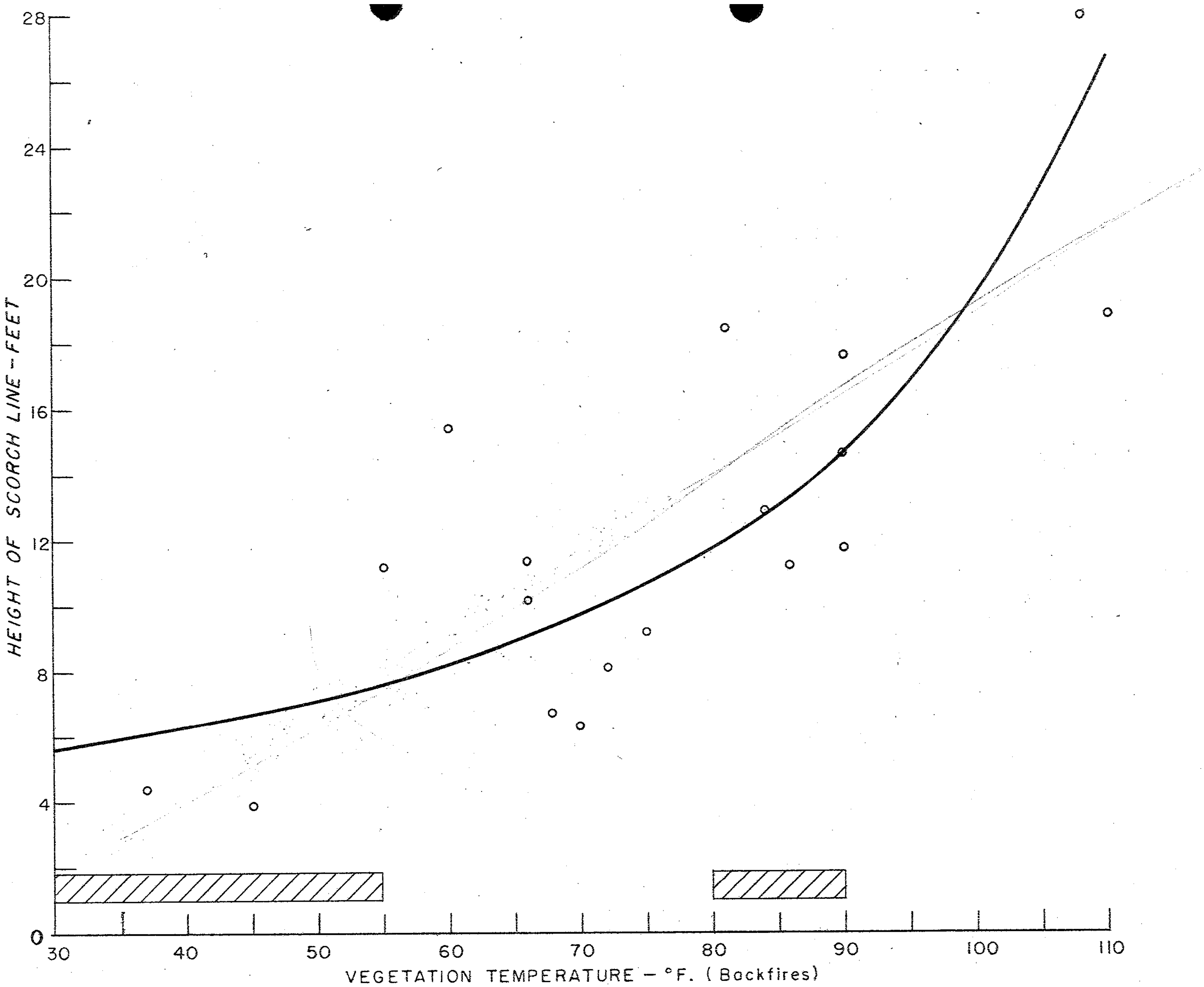
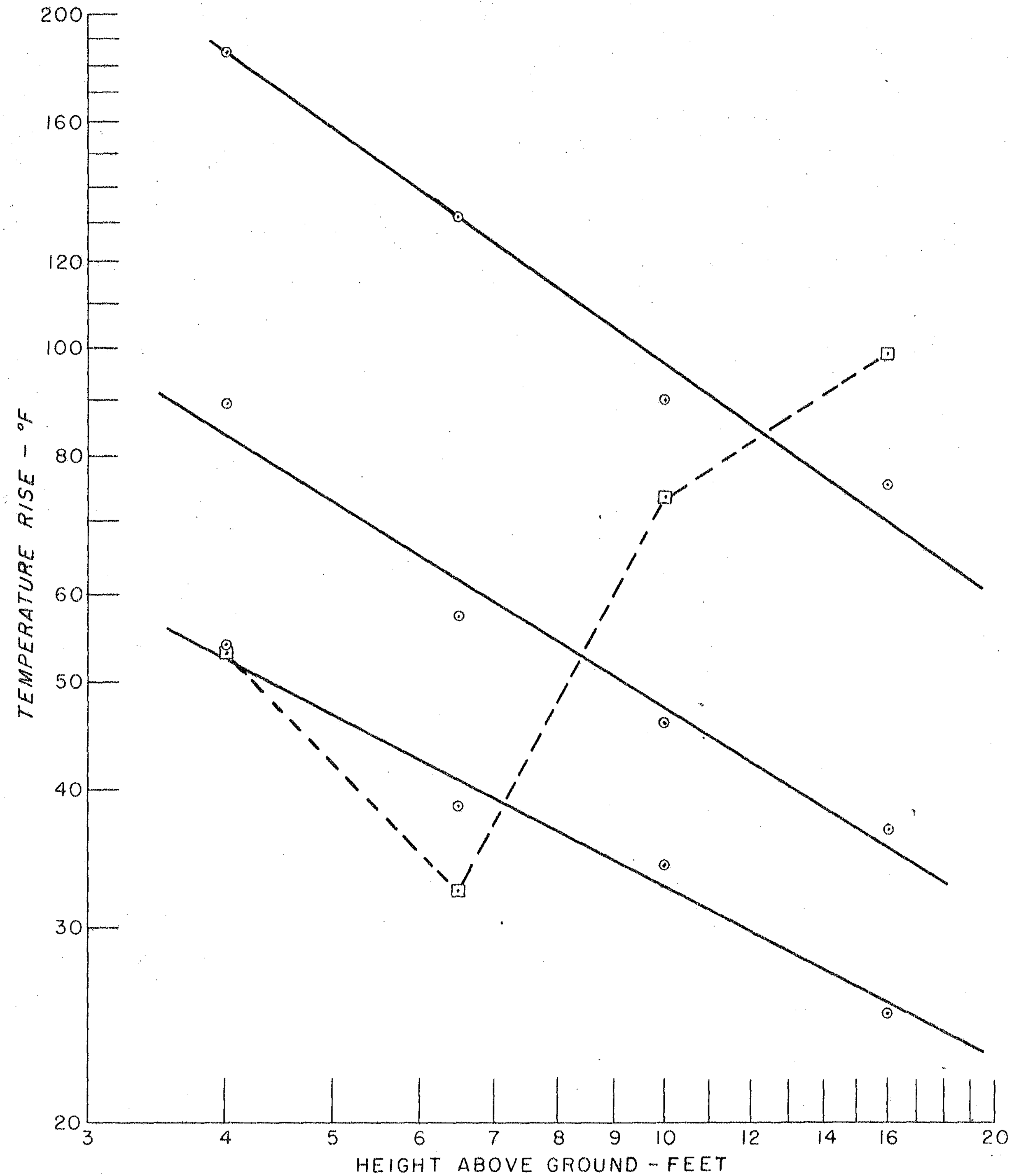

HEIGHT OF SCORCH LINE - FEET
VEGETATION TEMPERATURE — °F. (Backfires)
0
4
8
12
16
20
24
28
30
40
50
60
70
80
90
100
110

Figure 9.—Temperature rise with height of fires.



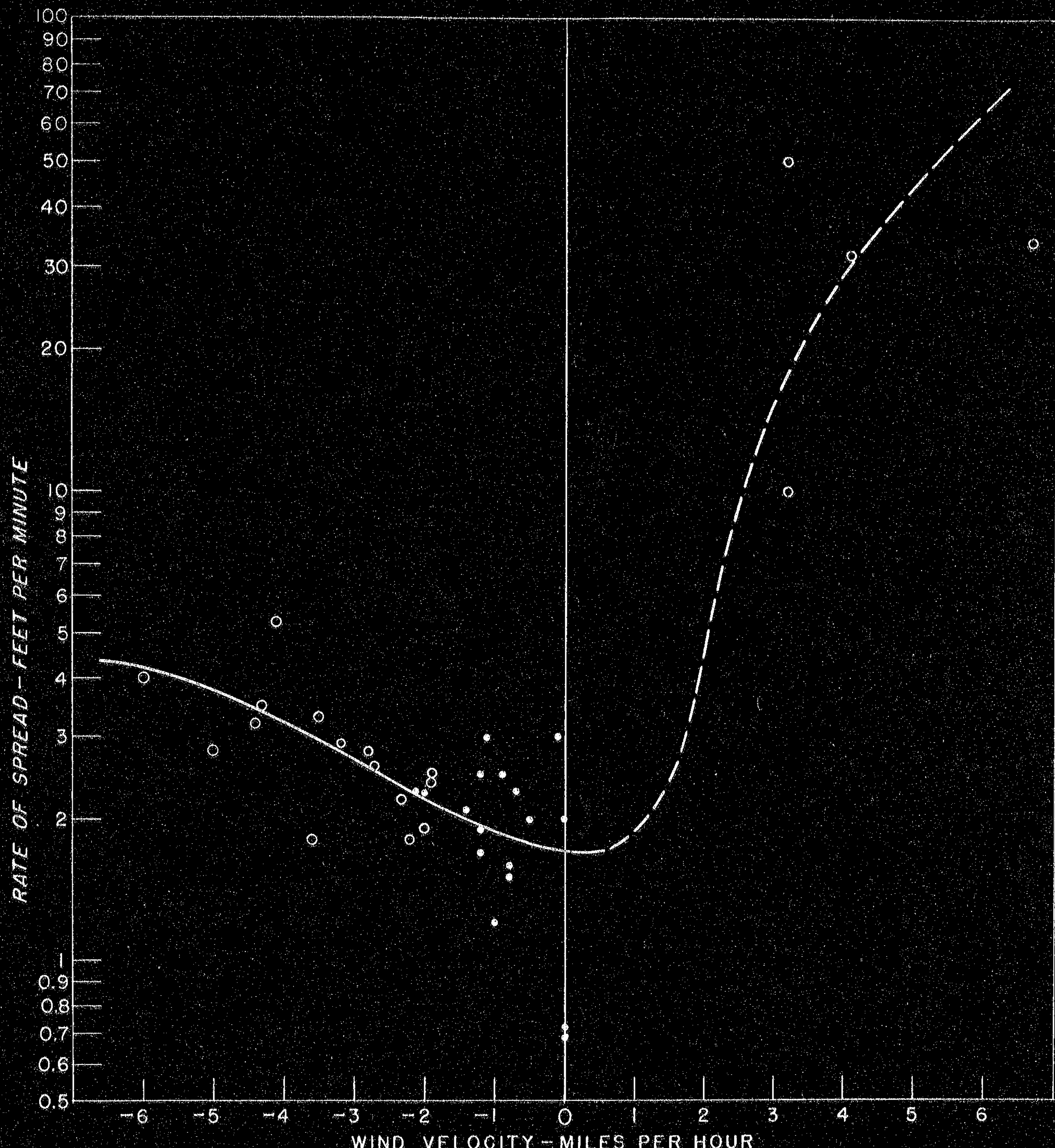
TEMPERATURE RISE - °F
200
160
120
100
80
60
50
40
30
20
3
4
5
6
7
8
9
10
12
14
16
20
HEIGHT ABOVE GROUND - FEET

height of scorch for the loblolly fires after all fires had been reduced to the same intensity. There is considerable scatter of the plotted points but this is not surprising considering the several sources of error. Some error is involved in estimating the average height of scorch. Another source of error results from variations in fuel, wind, and hence fire intensity in different parts of the plot. However the agreement of the experimental points with the theoretical curve is close enough to indicate that this curve describes the relation between height of scorch line and vegetation temperature. A few more observations are needed for cold weather fires and very hot weather fires.

Rate of spread

Although rate of spread was not considered a high priority problem in the present studies, some rate of spread measurements were needed in the fire intensity work. These are plotted in Figure 11 which shows rate of spread plotted as a function of wind velocity. It is helpful to think of backfires as burning in winds with a negative velocity. This point of view results in a complete wind velocity scale ranging from negative velocities through zero up into the positive or headwind velocities. Figure 11 illustrates the interesting fact that rate of spread of backfires increases with increasing wind velocity. Field men have noticed this relationship for some time. Probably minimum rate of spread occurs with a very light headwind, somewhere between 0.3 and 0.5 miles per hour. Fires burning in an absolute calm will tend to burn as backfires because they create an

Figure 11.--The relation between rate of spread and wind velocity. Velocities of headfire winds are considered positive, and velocities of backfire winds are considered negative.


RATE OF SPREAD - FEET PER MINUTE
WIND VELOCITY - MILES PER HOUR
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6

indraft with a velocity from about 0.3 to 0.5 miles per hour. The open circles represent measurements in the longleaf area (Figure 2) and the solid circles represent measurements in the loblolly area (Figure 2). The open circles in Figure 11 represent measurements obtained on the longleaf area shown in Figure 3 and the solid circles the measurement in the loblolly area of Figure 1.

SUMMARY

The lethal temperature of the tissue in the critical parts of a tree is in the neighborhood of 140 F. This figure is very low in comparison to the high temperatures (ranging up to 1500 F) of the hot gases composing the flames of a fire. It is the low value of the lethal temperature which makes the initial vegetation temperature one of the most important factors of fire damage and mortality.

Copper-constantan thermocouples inserted in the terminal buds of longleaf seedlings show that the temperature rise of such seedlings is surprisingly small when a fire passes over them. The temperature rise in the heavy buds of vigorous seedlings with dense needle growth may be only 30 F or less. Such seedlings could survive fire on a hot day when their initial temperatures might be as high as 110 F. Small seedlings may have a temperature rise of 100 F or more. They would survive a fire only on a very cold day.

Most of the mortality in young longleaf pine from 1/2 to 4 feet in height is undoubtedly caused by the girdling effects of fire near the base of the main stem. Headfires probably cause some girdling

effects higher on the stem, but there is probably little difference in the effect of headfires and backfires on trees in this size class.

Backfires are hotter than headfires in the zones within 10 inches of the ground in grass fuels. The latest measurements also indicate that headfires spreading before a strong wind are cooler near the ground than headfires spreading before a light wind. The maximum temperature rise for backfires in grass fuels about one foot in depth occurs at a height of 4 inches. For headfires the maximum is near 12 inches, but the height of maximum temperature rise for headfires may depend somewhat on wind velocity.

The effect of initial vegetation temperature is just as important for trees 100 feet in height as it is for longleaf seedlings in the grass, because mortality and injury from fires in mature timber, as well as in reproduction stands, is determined mostly by the heating effects in the buds, needles, and small branches. Initial stem temperature is equally important in those size classes and species in which girdling is likely to occur.

The temperature of the gases above a fire decreases rapidly with height. The temperature rise above backfires has been measured with thermometers having bulbs of about the same heat capacity as loblolly buds. The relation between height of scorch line, vegetation temperature, and fire intensity has been determined and the theoretical prediction seems to be in good agreement with the results of the field measurements.

Variations in the rate of temperature decrease above fires have been found which may furnish an important clue to the peculiar behavior of large fires including the "blow-up" fire. It seems likely that the stability of the atmosphere is an important factor in fire behavior.

The rate of spread of backfires increases with wind velocity and for velocities up to 5 or 6 miles per hour it is directly proportional to wind velocity.

SECTION II - The Role of Prescribed Fire in the Life Cycle of Longleaf and Loblolly Pine

The physical structure of the southern pines and their growth habits are such that it is highly probable that their evolutionary development was determined to a large extent by fire. Longleaf pine especially seems to have adapted itself to fire so effectively that fire is now an essential ecological element for its perpetuation. Its bark has a high insulating value and is considerably less inflammable than the interior wood. The thick heavy buds have a high capacity for heat as well as a down-like layer of insulating tissue. In addition they are surrounded by a heavy sheath of protecting needles, especially in the young trees. Seedlings keep their terminal buds for several years in the relative cool zone (Figure 6) next to the ground until the buds and stem have thickened and acquired a heat capacity which will permit them to withstand higher temperatures.

The other southern pines seem to be at least partially adapted to fire but have developed different growth habits and mechanisms than longleaf for tolerating fire. All have the characteristic insulating "fireproof" bark. Shortleaf and pond pine are capable of sprouting. Young Slash and loblolly pine have very rapid growth rates which permit them to spend a minimum amount of time in the most vulnerable size classes.

Our work so far seems to indicate that if prescribed fire is to be used at all it should be used frequently. From what we know now of the heat transfer process, it is probable that 3 or 4 prescribed fires in 10 years would do less damage than one prescribed fire in 10 years. One of the main benefits of prescribed burning is fuel reduction so that subsequent wildfires will do as little damage as possible. However this is just as true for prescribed fires as for wildfires. In order that a given prescribed fire have the benefit of the "insurance" established by the preceding prescribed fire, it must follow that fire by a comparatively short interval, probably not longer than 3 years, although the actual time would depend on rate of fuel accumulation and cost of burning. The cost per burn for frequent fires should be considerably less than for infrequent fires. Whether the total cost of a frequent burning schedule would be less than in infrequent schedule remains to be seen. A somewhat higher cost for frequent burning might be justified on the higher quality of protection obtained by the continuous removal of fuel and also on the more effective hardwood control.

Although more information is needed to determine the proper place of fire in the life cycle of longleaf and loblolly pine, setting up tentative specifications for the use of fire in pine stands may be helpful in bringing about a clearer perspective of this problem. The silviculturist should decide whether or not fire should be used in a given stand. The following suggested specifications are therefore

concerned primarily with the burning conditions and type of fire that should be used when burning is required in different stands. They will undoubtedly be modified as later studies are completed.

Briefly these suggested specifications for even aged stands are:

Loblolly

1. Reproduction stands from 0 to 25 feet in height

Silviculturists would recommend fire exclusion and intensive protection. This means that no fire would be used in loblolly stands for the first 10 or 12 years.

2. Stands from 25 to 35 feet in height

First burn for hardwood control and fuel reduction should be cool weather backfire with steady winds and dry surface fuel. Considerable plowing may be needed for this first burn. If subsequent burns are at periods not exceeding 3 years, parallel strings of flankfires in cold weather might be used to burn the stand in a short time. If the stand is surrounded by natural barriers little or no plowing should be needed. If subsequent burns are at periods of 4 or more years, they should probably be handled like a first burn.

3. Pole stands 35 to 50 feet in height

First burn same as 2 except that temperature requirements are not as critical. If subsequent burns are at periods not exceeding 3 years, parallel strings of flank fires in cool

weather or even headfires in cold weather (40° F or less) might be used. However more tests will be required to determine headfire intensities in light loblolly fuels.

4. Small sawtimber stands 60 to 75 feet in height and mature stands over 75 feet.

The use of fire for hardwood control is most effective in these older stands because the burns can be made in hot weather. Summer backfires with a vegetation temperature of 85 or 90° F and a fairly dry fuel may possibly kill hardwoods up to 4 or 5 inches in diameter (ground level). Repetition of such fires as soon as enough fuel has accumulated to carry fire may result in the kill of even larger hardwoods. However, after the larger hardwoods have been killed back (either by fire or other methods) the control of smaller hardwoods and fuel reduction could be more economically accomplished by faster spreading fires in the cool weather of other seasons. From Figure 10 it is doubtful if summer burning should be attempted if crown temperatures are much above 90° F. Even a low intensity fire could result in crown scorching under such conditions and might also kill patches of the cambium layer in pines in the main stem near the ground.

After the first one or two burns in a nearly mature stand, annual headfires with cool weather of late fall might be the most desirable burning schedule especially when the stands are surrounded by permanent barriers.

5. Stands to be regenerated

Our studies do not have much to contribute to the solution of this problem. With the possible exception of longleaf it has not yet been demonstrated that fire alone can maintain a pine stand. It may be that chemical or mechanical methods plus fire will prove more effective than fire alone in achieving the high degree of hardwood control needed at the time of regeneration.

Longleaf

1. Stands consisting of a scattering of mature seed trees and an inadequate stocking of seedlings

A later summer burn in a good seed year. A headfire in cloudy weather as cool as possible at this time of year will minimize damage to seedlings already established, but will cause some scorching of seed trees. In localities where there is a bird or rodent problem, burning might be more effective if done during the winter preceding seed fall. The Southern Station is working on this problem.

2. Stands consisting of a scattering of mature seed trees and an adequate stocking of seedlings in the grass stage

Work going on at the Southern Station should show when burning would benefit longleaf seedlings in the grass stage. Brownspot, hardwood control, and grass competition probably would be the chief reasons for burning. If burning is necessary, cool weather headfires should be more effective in brownspot

control than backfires. Headfires sweep across areas of scanty fuel which backfires will not burn. Also the higher scorch line of headfires destroys brownspot lesions which backfires do not reach.

If a high proportion of the seedlings are in the one and two year old class, burning might best be postponed a year. If this is not desirable because of brownspot or some other reason, headfires with a seedling temperature not above 50° F should be used. Table I indicates that headfire temperatures near the ground decrease with increasing wind velocity. Headfires with strong winds should therefore give the most protection to the seedlings. However, even with cold weather headfires a high proportion of the one year seedlings are probably killed.

3. Young stands with a high proportion of trees in the 1/2 to 4 foot class

No reason for burning unless the survival of brownspot infected seedlings in the grass is needed for adequate stocking. A fairly high proportion of the young longleaf 1/2 to 4 feet high is girdled in warm weather when fire burns the accumulated pine straw at the base of the stem. Headfires and backfires seem to do about an equal amount of damage in this size class, although backfires may cause slightly higher mortality for the smaller trees, and headfires may produce somewhat greater mortality in the larger trees. If such a stand must be burned the cold weather headfire should be most economical, although defoliation

may cause some growth rate loss in the trees which have put on height growth after emerging from the grass stage.

4. Reproduction stands 5 to 25 feet in height

Either fire exclusion or frequent use of fire. In areas of low fire occurrence, exclusion of fire might be best if hardwoods are not a problem. If fire occurrence is high, then backfires at intervals not exceeding 3 years might be justified - especially if there is an understory of inflammable evergreen brush. Cold weather headfires would cause little mortality in this size class, but defoliation would retard growth somewhat.

5. Stands exceeding 25 feet in height

Same burning schedules as for 2, 3, 4, and 5 in loblolly except that temperature and fire intensity requirements are not so critical.

In concluding this section it may be desirable to review the status of several questions in prescribed burning which were brought up during the early part of this study. Listed briefly, these questions were:

1. What is the maximum or critical amount of fuel which can accumulate in a loblolly stand before it is likely to result in a serious loss at the time of year when wild fires are most likely?
2. How small can loblolly be and tolerate burning?
3. What is the season of the year that burning can best be accomplished?

4. Can light fire be used to thin stagnated stands of young loblolly?

5. What are the possible uses of fire in eliminating young loblolly and slash from sites better suited to longleaf?

We can give general answers to these questions now, and should have more definite and specific answers within the next two years. The following comments are based not only on our own work but also on observations of the results of the prescribed burning on the Francis Marion National Forest in the past three years and on some of the studies on the Santee Experimental Forest.

1. The rate of fuel accumulation is most rapid in the years immediately following a fire. This applies not only to fuels such as pine straw, dead grass, and litter, but also to living fuels such as gallberry and myrtle brush. After four or five years the rate of decomposition of the dead fuels nearly offsets the rate at which new fuel is formed. The evergreen shrubs with their inflammable leaves put on most of their sprout growth in the years immediately after a fire. All of this indicates that the protection of "insurance" established by a prescribed burn does not last very long. It is likely that a spring or summer wild fire on a hot day in the third year after a prescribed burn could do serious damage in a loblolly stand as much as 50 feet in height. This again points to a schedule of frequent prescribed burns.

2. The lower limit on the size of loblolly which can be successfully burned is probably about 25 or 30 feet. However the limit seems to be an economic or practical one. If time and expense is not considered, the limit would be much smaller. A low intensity fire on a cold day may produce a scorch line less than 3 feet in height, so trees 6 to 8 feet in height should survive such a fire. However there seems to be little reason for burning such stands.

3. The time of year for burning will depend to a considerable extent on the purpose of the burn. First burns for fuel reduction in a heavy fuel would require the cool weather from mid-December to late February. If a frequent burning schedule (2 or 3 years between burns) is planned, the period for subsequent burns in light fuels might be lengthened to as much as 6 or 7 months, possibly from October to May. However the length of this period would be less for the younger stands. Except for a period during the season of rapid growth, there seems to be no evidence as yet that dormancy of the trees is an important factor in fire damage. At the beginning of the growing season, the succulent and unprotected candle-like growth at the ends of the branches seems very susceptible to fire. Burns to kill large hardwoods should be most effective in hot summer periods and have been discussed in some detail on the preceding pages.

4. Our studies have not given much information on the use of fire for thinning stagnated stands of young loblolly pine. However, they have shown that very dense loblolly thickets are almost fireproof

throughout the winter months. Unless the winter is unusually warm or dry, the dense shade and lack of air movement keep the fuels moist until transpiration in the warm weather of spring can contribute to the drying process. Unfortunately these dense reproduction stands seem to favor the buildup of the severe whirling type of fire which occurred more frequently this spring (1950) than in previous years.

We have noticed that the suppressed thin barked trees are often killed by girdling when these stands are burned. However, silviculturists state that these suppressed trees offer little competition to the dominant trees of the stand and will die anyway.

5. Fire should be even more effective in preventing the encroachment of slash and loblolly seedlings on longleaf sites than in controlling hardwoods because these seedlings do not sprout. Young pond pine seems to sprout as readily as hardwoods but apparently presents no problem.

SECTION III - Plan of Work for 1950-52

Introduction

The general objectives of work for the next two years will be similar to the objectives of the initial studies. This later work will therefore be primarily investigations of the fundamental nature of fire behavior and the way in which the effects of fire are brought about. This latter field is midway between the fields of fire behavior and fire effects and up till now has been given the highest priority. Because we believe that we now understand fairly well the mechanism of heat transfer and the way it produces lethal effects on living trees, it may be found that emphasis can be directed to some of the more complex problems of fire behavior. However, it is doubtful if any hard and fast line can or should be drawn between groups of problems which should be given highest priority. Priorities should change as work progresses and new ideas develop. Perhaps a guiding criterion would be to keep our energy currently directed on those problems for which solutions are definitely needed and which within the limits of our personnel and equipment we believe we can make good progress. However the value of such a guiding criterion would depend on a careful formulation of problems. Before the need of a solution of a problem can be evaluated the problem must first be clearly defined and formulated. Also, the major part of the solutions of some problems may often consist of nothing more than their careful formulation.

The studies discussed in the preceding section were for the most part small scale experiments designed to test important theoretical leads and clues as to the basic nature of certain aspects of fire behavior and intensity and their relation to the living tree. Some of these studies are now completed and others are far enough along to extend them to larger scale field trials and application. These large scale studies will be an important part of future work.

Outline of Problems

The following outline presents in a condensed form the work proposed for the next two years on the high priority problems (as they appear at the present time). Discussions of each problem are given after the outline.

A. Laboratory studies

1. Make precise determination of lethal temperature for loblolly pine needles and buds. Determine effect of exposure time on lethal temperature.

2. Determine susceptibility of different hardwoods species by stem size and age to fire.

B. Large scale field studies of fire intensity

1. Determine effectiveness of prescribed burning as a fuel reduction measure by measuring fire intensity in fuels accumulating after different length of time have elapsed since initial burn.

2. Investigate methods for lengthening season of prescribed burning.

3. Determine whether or not fast spreading headfires and flankfires can be used for prescribed burning in loblolly pine in light fuels and cold weather.

4. Determine the burning cycle (that is, the frequency of prescribed fire) which should give the maximum expected net economic gain.

C. Start work on the cause and behavior of severe fires.

D. Start detailed study of fuels and their relation to fire intensity. This study would be carried on simultaneously with those listed under B.

E. Make field tests to determine effect of vegetation temperature on size of hardwoods killed by fire.

F. Continue intensive small scale experiments as needed to supplement work on larger scale studies.

Discussion of Problems

The purpose of the following discussions is to present a formulation of each problem in the preceding outline (insofar as it is possible to do this now), to present and evaluate the needs for solutions, and to estimate the possibilities for progress on these problems. Detailed working plans for problems A-1 and A-2 are given in Supplements 1 and 2. It is doubtful whether detailed working plans should be prepared too far in advance of actual field or laboratory work.

If problems have been carefully formulated, the detailed plans might be prepared to best advantage just before work on a given study is started. For this reason the working plans for the rest of the problems will be prepared when we are ready to start actual work, presumably before the end of this year for studies B, C, and D. For studies of a straightforward nature that can be completed in a comparatively short time, such as some of the small scale experiments which would come under F, it might be best not to prepare working plans at all. The time required to prepare the plans would be out of proportion to the time needed to do the actual work.

A-1. Lethal temperature of loblolly pine needles and buds

One of the most important factors associated with the damaging effects of fire is the lethal temperature of plant tissue. The lethal temperature may be defined as the temperature at which irreversible changes take place in the living cells which eventually result in the death of these cells. If enough cells are affected, death of certain parts of the plant or even all of the plant results. The relative effects of different initial vegetation temperatures on height of scorch line, on girdling of hardwoods, and on the mortality of longleaf seedlings are all controlled by the value of the lethal temperature. This value is usually assumed to be about 140 F and this is the figure that we have used in our computations so far. However, it varies with different types of plants and there is some evidence that the 140 F figure may be too high for loblolly needles and buds. Also,

the value of the lethal temperature may vary somewhat with exposure time. For example an exposure of 5 or 10 minutes at a temperature of 130 F might be equivalent to an exposure of 1 minute at 135 F. The shape of the theoretical curve in Figure 10 will be determined by the value of the lethal temperature.

Owing to the importance of the lethal temperature and its possible variation with exposure time, its value as well as its variation with exposure time should be precisely determined. The details for doing this work for loblolly needles and buds are given in the working plan in Supplement 1. The estimated time is about 20 man days.

A-2. Susceptibility of hardwood stems (by size and age) to fire

The initial temperature of the cambium layer is probably one of the most important factors in the killing of hardwoods by fire. If so, then fires of equal intensity should kill larger hardwoods in hot weather than in cold weather. This being the case, it should be possible to construct a family of curves (one curve for each species) each of which is analogous to the curve in Figure 10. These curves would show relative size of hardwoods killed at different initial temperature for fires of equal intensity. However the time required for the cambium layer to reach the lethal temperature depends not only on the initial temperature but also on the rate of temperature rise of the cambium when the stem is enveloped by hot gases. In turn the rate of temperature rise will be determined by the heat conductance of the bark layer, stem size, and gas temperature.

When the relative heat conductance of stems of different sizes and ages has been determined, the curves mentioned in the preceding paragraph can be constructed. The specific problem will therefore be to determine the relative heat conductance of the bark of hardwood stems by size and age. The working plan for doing this is given in Supplement 2. The estimated time is 25 man days.

B-1. The effectiveness of prescribed burning as a fuel reduction measure

One of the main benefits of prescribed burning is fuel reduction. Foresters have thought of fuel reduction as a type of insurance against damaging wild fires. The price of the insurance is the cost of burning plus some damage resulting from prescribed fire. Balanced against this cost is a reduction in the expected loss which wildfires would have caused had there been no fuel reduction. Other benefits should also be weighed against the cost, but they are discussed separately.

The fuel reduction benefit has its maximum value during the first year after a prescribed burn. After the first year, accumulating fuels bring about a progressive deterioration of the initial insurance. In loblolly stands the insurance probably has a negligible value after five years have elapsed.

The specific problem here is to measure the buildup in fire intensity as the fuels become progressively heavier after a prescribed burn. The experimental burns should be on a fairly large scale so that the fires would reach their full intensity. For backfires this might be from 1 to 2 acres and for headfires 5 to 15 acres. If it is

found that smaller areas can be used so much the better. Burns would be made in fuels 1 year old, 2 years old, and 4 years old, and intensities compared with those in unburned fuels. Because age of fuel is a poor indicator of amount of fuel and its characteristics, fuel measurements would be an important part of this study which would tie in closely with study D.

A determination of the buildup in fire intensity in fuels accumulating after a prescribed burn would be an important step in finding how often loblolly stands of different ages and sites should be burned, but would not give the complete answer. This would require the additional work under B-4.

Probably a working plan for this study should not be written until the possible study areas have been carefully examined and the scope of the study decided upon. For example, it could be carried on for a number of size classes varying from young reproduction stands to mature stands. Similarly it could be extended to a number of sites with different fuel characteristics. At present it would seem advisable to limit the study to three size classes of fully stocked loblolly stands; young stands 25 to 30 feet in height, stands 45 to 50 feet in height, and small sawtimber stands 65 to 75 feet in height. Possibly the last could be omitted. The study should probably be confined for the time being to the site which field men consider typical of the most troublesome fuels. This last requirement might be met in a general way by avoiding those loblolly stands growing

on the sandy ridge longleaf sites, and also avoiding those stands on low moist sites near creeks and swamps.

B-2. Lengthening the season for prescribed burning

The present period for prescribed burning in loblolly is only two or three months in midwinter. Furthermore there may be only a few good burning days during this period, and in some years burning may be almost impossible. This condition presents a serious problem for the field men responsible for burning.

There are several factors which make burning hazardous at other times of the year, but the most important of these is undoubtedly high temperature. High temperature can be offset only by low intensity fires. This requires light fuels and fuels can be kept light only by a schedule of frequent burns. It would then appear that lengthening the prescribed burning season would require burning at fairly short intervals possibly not longer than three years. When the understory hardwoods are killed back, considerably more light reaches the ground. This means more rapid drying of fuel after rains. Also grass and herbaceous plants start coming back and these burn readily when they cure in late fall. If successive burns are not too far apart the fires will be of low intensity. It might be possible to extend the burning season for nearly mature stands to 8 or 10 months and to 4 or 5 months for younger stands.

Most of the solution to this problem will come from the solution of the preceding problem, B-1. However, it will require some additional

work such as burning during the fall and spring months, and observations of the response of fuels to drought periods. A working plan for this study might best be written after actual field work on the preceding problem (B-1) has been started.

B-3. Possible use of fast spreading fires in prescribed burning

The job of prescribed burning could be greatly speeded up and costs reduced if fast spreading headfires could be used instead of backfires. The nature of this study is similar to B-2, but the purpose is quite different. The specific problem would be to find methods for utilizing to the fullest extent the small number of cold days (and nights) in the winter when the fuels will burn. Measurements would be made of the intensity of headfires and flankfires on areas with different amounts of fuel. From the results of these measurements it should be possible to specify the conditions (such as temperature, height of stand, amount of fuel, and moisture content of fuel) under which fast spreading fires could be safely used for prescribed burning.

It has been found on small test burns that the stability of the lower atmosphere has a pronounced effect on the behavior of small fires, and its effect may be even more important on large fires. Burning with headfires should be safest when the air layers near the ground are stable. During the winter months the air is usually stable by 4 p. m. on cloudless days. It becomes increasingly stable during the night. Night burning with backfires is considerably more difficult than day burning and to a considerable extent has been abandoned in

favor of day burning. However from the standpoint of low temperatures and a stable atmosphere, night burning has definite advantages if the fuel moisture is not too high. For fast spreading fires on large blocks, night burning might not have the difficulties that are encountered with slow spreading fires where the men must spend considerable time in dark woods.

B-4. Frequency of prescribed fire for maximum expected economic gain

This would be a study in economics and with the exception of preliminary planning work it is doubtful that any work will be done on this problem within the next two years. It would be an integrative type of study, hence its solution would first require the solution of almost all of the other problems in the preceding outline. Additional information would also be required such as values at stake in stands of different ages and sites. Required also would be knowledge of the effect of fire on mortality and growth rate loss as well as information on expected weather and fire danger conditions.

From the standpoint of the possible contribution and progress we could make on this study during the next few years, it would have a lower priority than any of the other studies listed here.

C. Cause and behavior of severe fires

Until recently it has been thought generally that fire behavior was determined by the quantity of fuel and its characteristics, fuel moisture, fuel temperature, wind velocity, and topography. Although the relations of certain aspects of fire behavior (such as rate of spread or fire intensity) to the above factors are not precisely

known, it has been assumed that such relationships exist and that their evaluation required only the research effort to do the job. This point of view now seems open to question. The stability of the atmosphere itself may be a more important factor affecting fire behavior than any one of the preceding factors. If this proves to be true, then rate of spread and fire intensity for large fires will not be satisfactorily accounted for in terms of the familiar fire behavior variables. Nevertheless the possibility that turbulence may be an important factor in fire behavior is not a new idea, and its importance in influencing fire behavior has undoubtedly been noticed by a number of field men. Turbulence and "vertical air currents" have been recognized for some years as having an adverse effect on fire behavior.

Like chain reactions in general, the combustion of forest fuels exhibits certain levels of intensity with sharp transition zones between the different levels. The lowest level is the frequent low intensity fire which consumes the fuel on the ground. A second level is represented by the fire which crowns in the understory evergreen brush. At a third level the fire goes into the crowns of the overstory conifers with a sudden increase in intensity and rate of spread.

To account for the behavior of the so-called "blow-up" fires which are most likely to occur where the topography is rough, it is necessary to assume that a fourth level of fire behavior exists which differs greatly from the fast spreading crown fire. Several suggestions have been put forth to account for the strange characteristics of these

fires. It has been suggested that large quantities of inflammable gases, distilled from the fuels in the path of a high intensity fire, may drift some distance before they ignite. However, this possibility is difficult to reconcile with the combustion process. A more logical concept is that this fourth level of fire behavior is analogous to a storm the physical characteristics of which may closely resemble the tornado or dust devil. The existence of vortex storms in the atmosphere requires definite energy conditions. When the potential energy of the lower atmosphere is high, it is unstable and the resulting circulating is such as to make this energy a minimum. For example, dust devils are formed when local convection from the strongly heated surface air over the desert creates a "chimney" in the cooler air above. If the lapse rate is high enough, the warm air rushing into the base of the chimney will create a rather violent whirl which may in some instances extend several thousand feet about the ground.

Possibly similar atmospheric conditions exist when fires blow up. When the lapse rate is high the potential energy of the lower air layers combines with the energy of the fire to create strong updrafts. When the fire reaches some critical size the updrafts are strong enough for the formation of a violent whirl. If the topography is rough a large whirl might ignite a whole slope or watershed in a short time. Wind velocities of from 50 to 90 miles an hour have been reported in exceptional dust devils. On large fires the velocities within the whirl should be considerably greater.

The marked change in fire behavior that often comes in early evening is strong evidence that the lapse rate is an important factor in fire behavior. This change in behavior is usually attributed to a rise in relative humidity and hence in fuel moisture. However it is doubtful if a rise of a few percent in fuel moisture could account for more than a small portion of the change. Also, it is not likely that the drop in fuel temperature could account for more than a minor fraction of the decreased intensity. The increase in relative humidity and fuel moisture and the decrease in fuel temperature must accompany the drop in the temperature of the lower layers of the atmosphere, but the most important factor may be the increase in atmospheric stability resulting from the temperature drop of the lower air layers. When the lower air is stable it has a dragging effect on the heated gases rising above the fire. These gases not only do work, or expend energy, as they lift their own masses through the stable air but they also spend part of their energy in dragging a part of the surrounding air upwards.

An entirely different condition exists when the atmosphere is unstable. The rising gases do not expend energy as they rise and may even acquire additional energy from the atmosphere. Their ascent upwards creates a chimney into which the surrounding unstable air near the ground is drawn. The potential energy of the lower air is then converted into kinetic energy as it enters the chimney initially created by the fire. When the updraft is strong enough whirls develop.

The critical combination of lapse rate, rate of energy release from the fire, and wind velocity required for the vortex formation are not known. Lapse rates are highest on calm sunny days. However, it is doubtful if large whirls could form over fires burning in an absolute calm in flat country. Neither would they be so likely to form on fires burning with a high wind, because a strong wind tends to lower the lapse rate and presents certain other barriers to vortex formation. The most favorable condition for the whirling type of fire in flat country seems to be a calm sunny morning followed by light to moderate winds during the afternoon burning period.

For fires burning in flat country, it is probably the lapse rate in the first 400 or 500 feet above the ground that has the most important effects on the fire. This should not be true in areas of rough topography where fires might travel up steep slopes for several thousand feet. Depending on the elevation differences the lapse rate up to heights ranging from 2,000 to 5,000 feet may be important. The behavior of whirling fires burning in rough country would be much more complex than those in flat country. Perhaps too much emphasis should not be placed on the whirling characteristics of these severe fires. The lapse rate could have a pronounced effect on the draft of fires which might never reach the whirling state.

A detailed working plan for this study probably should be written after we know more about the methods and approach we should use. It will be considerably different than any fire study we have made in the past. Perhaps the problem of the cause and behavior of

severe fires may be regarded as solved when it is possible to predict or anticipate the transitions between levels of fire behavior. It is desirable to know how rate of spread and fire intensity within a given level are related to the fuel and weather variables, but this information may be of secondary importance. It would be better to know when a ground fire is likely to change suddenly to a crown fire, or when a crown fire is likely to change to a more dangerous whirling fire. The most effective suppression methods and fire fighting techniques may differ so widely between levels of behavior that variations in intensity and rate of spread within a level may be of less importance than we have previously thought. The severe fires this spring which occurred within a radius of 50 miles of the Charleston airport may give us considerable information to start from. The Weather Bureau station at this airport has daily upper air temperature readings from ground level up to a height of 23,000 feet. We are primarily interested in the lapse rate up to a height of about 600 feet, so the airport readings are not altogether suitable for our purpose. However they are the best we have at present, and on the fires we have been able to check so far the airport readings have indicated that the lapse rate has a marked effect on fire behavior.

The next steps would be a few preliminary tests on actual fires; possibly two or three fires would be enough. The areas selected would be of low value yet have a high volume of fuel such as would be found in some of the "oceans" or "bays" of the coastal plains. Such areas are difficult to ignite but when once ignited

they burn with a high intensity fire. The test fires should be 25 or 30 acres in size and roughly circular in shape. The Charleston Airport readings have already indicated that violent whirls may develop when the lapse rate is twice that of the dry adiabatic. For this reason one or more tests should be made when the lapse rate is at least twice that of the dry adiabatic rate. To encourage whirling, the area would be lighted around its entire perimeter. Measurements of the lapse rate would be made an hour or so before the fire up to a height of 600 feet. The simplest equipment for the part of the experiment might be a lightweight thermograph on a captive balloon. Measurements would be made of the barometric pressure drop near the center of the fire by means of an insulated barograph. If a whirl develops and if the barograph is located somewhere near the center of the whirl, then the velocity in the outer part of the whirl can be estimated from the pressure drop. Motion pictures of the fire would be made from a station about 1/2 mile away. The preceding test would be repeated in a similar area on a day when the fuel moisture, wind, and temperature were comparable to that of the previous test, but with a lower lapse rate.

The preliminary tests are simple in principle but would require considerable preparation andequipment. It would be desirable if they could be made this summer but this will not be possible.

The next step in the study would be a detailed theoretical analysis which would include a study of the dynamics of vortex type storms (tornadoes, hurricanes, and dust devils) and their application

to the behavior of severe fires. A great deal has been done on the mathematical theory of these storms. This part of the study may therefore be mostly a job of modifying and applying what is already known to our particular problem. This part of the work would also include an analysis of critical values of the variables involved in the chain of reactions in the buildup of a severe fire. For example, it may be found that even with a high lapse rate a fire will not reach the blow-up stage until the rate of energy release has reached a certain critical value. In turn this rate of energy release will depend on variables such as quantity of fuel, rate of spread, and fuel moisture. Stated in a different way, fires may blow up when comparatively small if the lapse rate is high enough, but they may not blow up until quite large if the lapse rate is low. Perhaps they might never blow up, regardless of size if the lapse rate is below a certain critical value.

The behavior of severe fires is a high priority problem and its solution may be necessary before a satisfactory fuel type rating system can be developed. This may also be true for the evaluation of the effectiveness of prescribed burning as a fuel reduction measure when severe burning conditions occur. If the stability of the lower atmosphere proves to be an important element of fire behavior, our chances for progress on this study are good.

D. Fuel studies and a fuel type rating system

The study of fuels and their relation to fire behavior is one of the high priority problems. Figures 12 to 15, as well as Figures 1 and 2, are photographs of some of the more important fuels on the Francis Marion National Forest. These are not typical of all fuels in the southeastern coastal plains but from the standpoint of the range of fire behavior they are fairly inclusive. Fuels in the slash-longleaf type farther south are heavier but the fuels in dense stands of young slash resemble those shown in Figures 12 and 13.

Figure 12 shows a dense stand of loblolly about 15 years old in which there are few understory hardwoods. The needles make a compact mat on the ground which is one of the least inflammable types of fuel. Figure 13 shows a similar stand with a dense understory of hardwood brush. Pine needles draped over the brush decay slowly and their arrangement makes an inflammable fuel. This condition is more serious when the hardwood brush is gallberry and myrtle. Figure 14 shows how the stand in Figure 13 appears in late June after a prescribed burn in the previous winter. Figure 1 (Section I) shows a more open loblolly stand about 10 years old in which grass and grass-needle mixtures are the main fuels. Figure 2 (Section I) is a somewhat similar fuel type in an open longleaf stand. Figure 15 is a photograph of a more dense longleaf stand approaching sawtimber size. Periodic burns have kept the hardwoods small and the partial shade favors the growths of ferns more than grass. The fuels in Figures

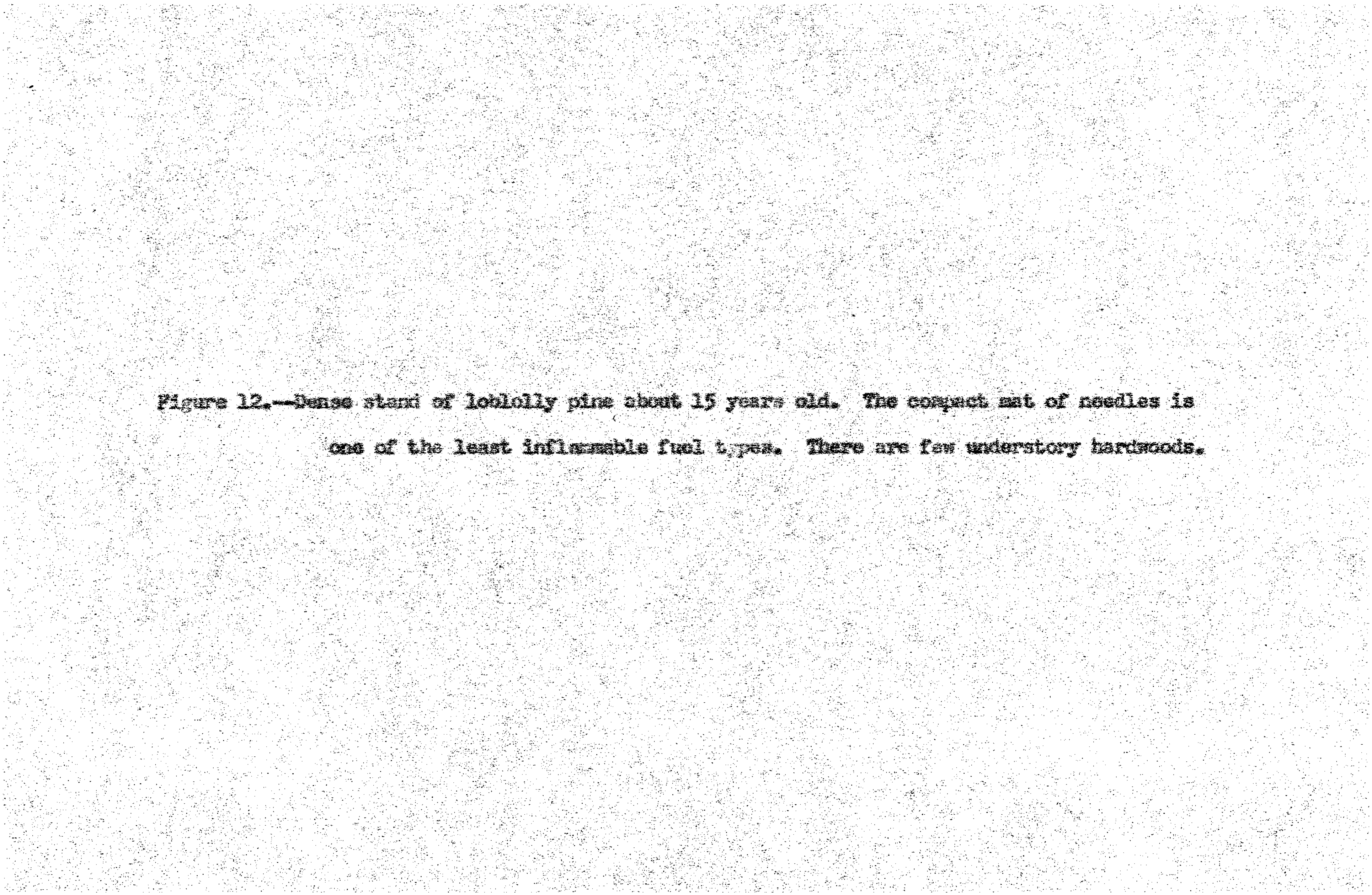


Figure 12.--Dense stand of loblolly pine about 15 years old. The compact mat of needles is one of the least inflammable fuel types. There are few understory hardwoods.

Figure 13.—Dense stand of loblolly pine about 15 years old containing numerous understory hardwoods. Draped needles make a highly inflammable fuel.

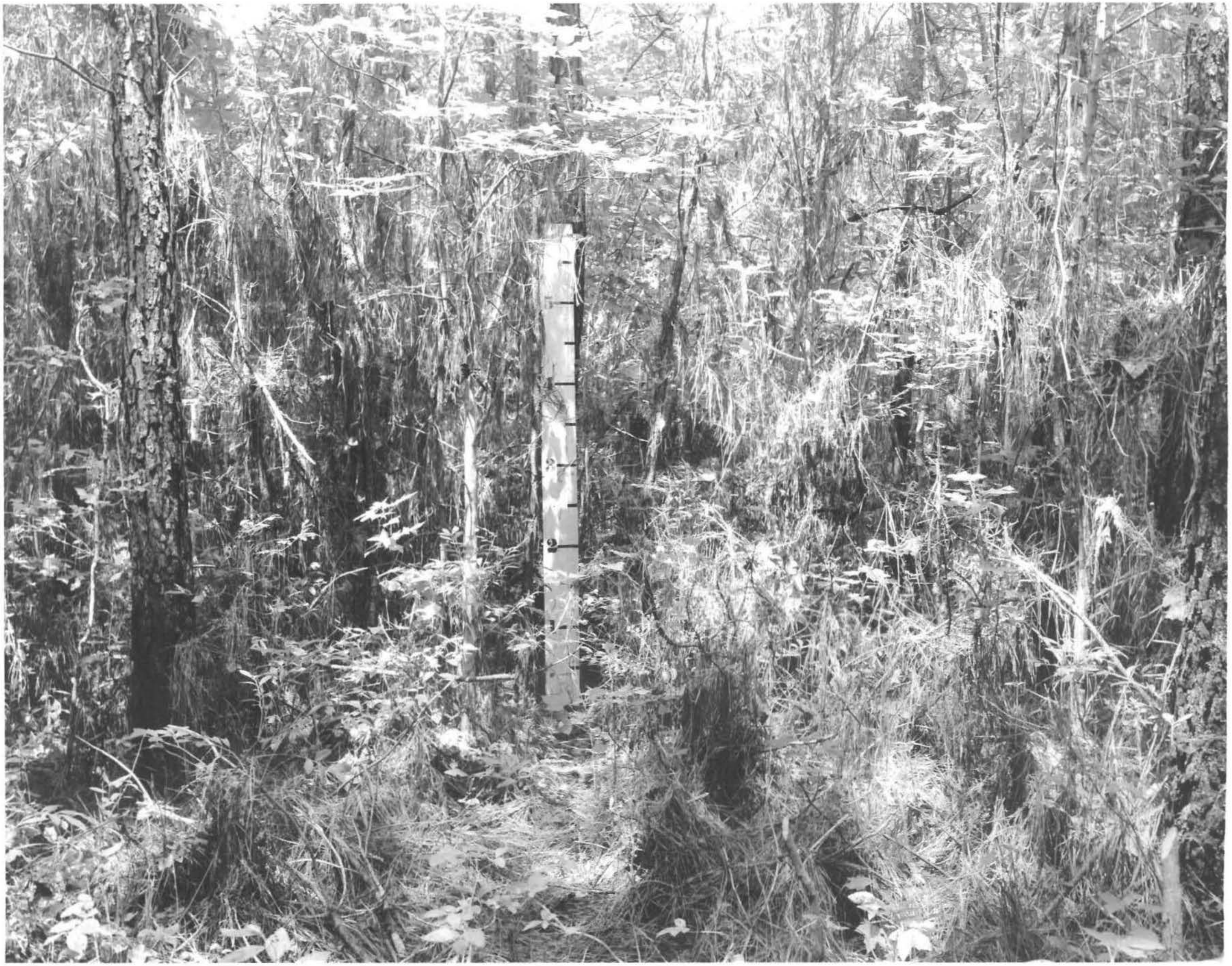


Figure 14.—The stand in figure 13 in late June. The area was prescribed burned during the previous winter.

Figure 15.—Periodic burns in this stand of longleaf pine have kept the hardwoods small. The partial shade favors the growth of ferns more than grass.

2 and 15 have high rates of spread and rapid response to drought, but are not a problem like the fuels shown in Figure 13.

A fuel type rating system may be visualized as one part of a more general fire behavior rating system. Fuels might be classified in a number of artibrary ways but the best classification method should be the one which fits best in a fire behavior rating system. This may require considerably more than a rating of fuels alone. For example, the response of different fuels to drought is undoubtedly important. Open longleaf stands with grass fuels predominating may approach maximum inflammability within 2 or 3 days after a heavy rain. In the same length of time fuels in dense loblolly reproduction and pole stands may be too wet to burn. However, as the drought progresses, the inflammability of the fuels in the thickets increases slowly and may not approach maximum inflammability for several weeks. When this condition is reached, these dense stands present a more serious problem than the faster drying fuels in open stands. It may not be possible to compare the behavior of fire in two different fuel types even when they are in the same stage of drought. For example, one of the most intense fires on the Francis Marion National Forest this year was in a young reproduction stand in which only an upper layer of the surface burned. The site was low and moist, so much of the ground fuel was not available for combustion. However, the lapse rate three hours before the fire started was about 1.1 F per 100 feet through an air

layer 400 feet thick or more. This is about twice the dry adiabatic rate and indicates a very turbulent and unstable air layer near the ground. This fire soon crowned and a large whirl developed over the head of the fire. In a strip about 200 yards wide down the center of the fire the foliage was completely consumed. Had the lapse rate been 0.5 F per 100 feet the fire might not have crowned. Even with the same wind, fuel moisture, and temperature, this might have been only a low intensity ground fire relatively easy to bring under control.

Suppose that the fire just described had burned in an open area with heavy grass fuels with a lapse rate of 1.1 F per 100 feet. Suppose again it burns with a lapse rate of 0.5 F per 100 feet (all other factors being the same). There would undoubtedly be a marked difference in the behavior of the two fires, but nothing like the difference which would occur in a dense stand where a high lapse rate could make available a new source of fuel (the tree crowns). More knowledge of the factors which determine fire behavior, and especially the transition between levels of fire behavior, may be needed before a suitable fuel classification system can be developed.

Fire fighting methods in some fuel types will depend not only on the expected fire intensity, but also on the degree of drought. For example, in certain moist and swampy sites which have underlying layers of organic matter, a plowed line may not hold fire after a prolonged drought. In this instance "resistance to control" depends

to a considerable degree on the state of drought of the fuel. On the other hand, "resistance to control" in a heavy grass rough over mineral soil is almost independent of drought.

An adequate fuel type rating system should be so designed that it is a component part of a fire behavior rating system. The most important function of this latter system would be to predict and anticipate different levels of fire behavior. Inasmuch as fire suppression measures may differ greatly from one level of behavior to another, the main value of a fire behavior rating system will undoubtedly be determined by how well it can predict these levels.

A detailed working plan for a study to develope a fuel type rating system could be prepared to best advantage after some progress has been made on the study of the behavior of severe fires which was discussed in the preceding section. Considerable work on fuels will be required in that study as well as on the fire intensity studies B-1, B-2, and B-3, but this work will not be primarily concerned with a fuel type rating system. The job of developing such a system could be done in connection with the fire intensity and behavior studies, or it might be considered as one of the basic studies in fire danger measurement work.

E. Initial temperature and size of hardwoods killed by fire (field tests)

The laboratory study A - 2 to determine relative susceptibility of hardwoods to fire should be followed up by actual field tests. The main purpose of these tests would be to obtain a field check on the

effect of initial vegetation temperature on the killing of different hardwood species by age and stem size. The first part of the study would require four pairs of plots, each plot being about one or two acres in size, depending on the number of hardwood stems available. All plots would be burned during January and February while the trees are dormant. One plot in each pair would be burned in cold weather with a bark temperature of 40 F or less. The other half would be burned in the warmest weather possible at that time of year with a bark temperature of 75 F or more. Fire intensity would be measured in the girdling zone (2-6 inches above ground). Before burning, about 100 hardwood stems would be selected on each plot ranging from 1/2 inch to 4 inches in diameter. Mortality would be recorded by size class.

The second part of the study would be identical with the first part except that burns would be made during relatively hot and cool weather in the summer. A detailed working plan should not be needed for this study.

CONCLUSION

At this time prescribed fire in loblolly pine has been confined mostly to one national forest, the Francis Marion. Whether or not fire should be used in other parts of the loblolly region will depend on the nature of local problems. For example, in the coastal plains of Southeastern Virginia wildfires are not a serious problem. Owing

to the climate and the habits of the local people, the fire occurrence rate is low. Burning for fuel reduction might not be justified there. The use of fire would be for such silvicultural purposes such as seed bed preparation and hardwood control. If these aims could be accomplished in other ways, fire might best be excluded from this part of the region.

The use of fire in the loblolly and shortleaf types of the Piedmont is doubtful. The clay soils of this region might rule out a schedule of frequent burns, and the rolling nature of the topography would make burning at infrequent intervals a hazardous venture.

The varying nature of the problems associated with the use of fire throughout the Southeast indicates that some of our work should be done in different parts of the loblolly region, such as Southeastern Virginia, the lower Piedmont, and areas farther west in Mississippi. However, with our present personnel we will have to confine most of our work to one part of the region. Because of the basic nature of most of the studies, the results should be applicable to regions other than the one in which the work was done. For example, basic information concerning the cause and behavior of severe fires should be as applicable to the forests of Oregon and Washington as to the forests of South Carolina. The fuels and tree species would be entirely different and the problem would be made more complex by rough topography in the western states. Nevertheless the same basic factors would be involved in the fires of both regions.